## Limnological Cycles in a Phosphatic Limestone Mine Lake

George K. Reid and S. Dexter Squibb

Since the early part of the 20th century "strip-mining" for land pebble phosphate matrix in south-central Florida has produced hundreds of "pits" which in time become filled with water. The greatest concentration of these lies in an area of some 6760 $km^2$ in Polk, Hillsborough, Manatee, and Hardee counties. The lakes produced vary in surface area, depth, and age and would, therefore, form the framework for very productive studies in comparative limnology.

To our knowledge, no intensive investigation of annual biogeochemical cycles in the phosphate pit lakes has been published. This report is a description of the limnological features and dynamics of one such lake.

### Phosphate Pit Lake

The basin of Phosphate Pit Lake (27°44′N lat. and 82°00′ W. long., Polk County, Florida) is an excavation resulting from mining of limestone containing phosphate rock "pebbles." These pebbles, ranging in size from less than 0.1 mm to over 30 mm, are pale orange to dark brown carbonate fluorapatite, with minor quantities of magnesium, manganese, uranium, potassium, sodium compounds, and others. The phosphorous content of the rock is in the form of tri-calcium phosphate ("bone phosphate of lime") ranging from 66-80 per cent $Ca_3(PO_4)_2$, or from 30-35 per cent as phosphorous pentoxide, which places this among the highest grade rock in the world (Shirley and Vernon, 1960). The material is a conglomerate of pebble, sand and clay deposited during the late Miocene or early Pliocene, and termed the Bone Valley Formation for the great array of fossil vertebrates contained in it.

The lake (Fig. 1) has a shoreline of 2,043 m, and the surface area is 28 ha, giving a shoreline development index ($D_L$) of 2.16. (Since completion of our study, reclamation efforts have reduced the surface area by about 2.4 ha). The sides of the basin are nearly perpendicular, resulting in no littoral zone of any extent. Maximum depth is 8.8 m with a mean of 7.9. Lake surface level (37 m above mean sea level) varied only 1.3 cm during 1962. The bottom

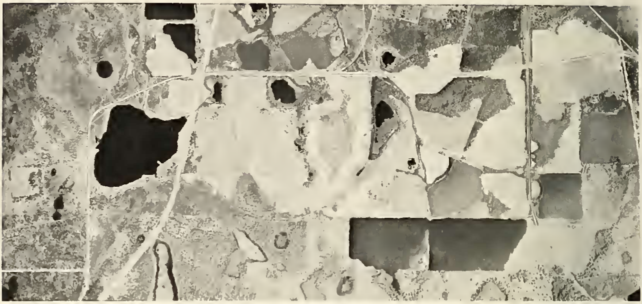

Fig. 1. Aerial photograph of Phosphate Pit Lake (extreme left) and nearby pits in 1958 (U. S. Department of Agriculture photo).

consists of very fine-grained flocculent silt (locally called "slime"), about 3 m thick, and supports no rooted plants. Natural vegetation surrounding the lake consists of forests of longleaf pine (*Pinus palustris*) and oaks; the turkey oak (*Quercus laevis*) and wire grass (*Aristida stricta*) are common. Willows (*Salix longipes*) have colonized the steep banks of the lake near the surface level. Precipitation and environmental temperature in the vicinity of the lake are shown in Fig. 2. This pit was mined during 1921, 1922, 1923 and then abandoned. It became water-filled probably within two years.

The station on Phosphate Pit Lake was occupied from 0830-1130 hr monthly during the period of study. In January, at the latitude of the lake, only one hour and thirty-five minutes of daylight prevailed before sampling was begun; in June some three and one-half hours of light had prevailed. This difference could have had some effect on certain data, particularly those pertaining to dissolved oxygen and carbon dioxide, chlorophyll, vertically migrating zooplankton, light transmission, and temperature.

## Methods

Phosphate Pit Lake was visited monthly from August, 1961, through October, 1962. One sampling station was established over the deepest part of the lake and was occupied at nearly the same clock hour on each visit.

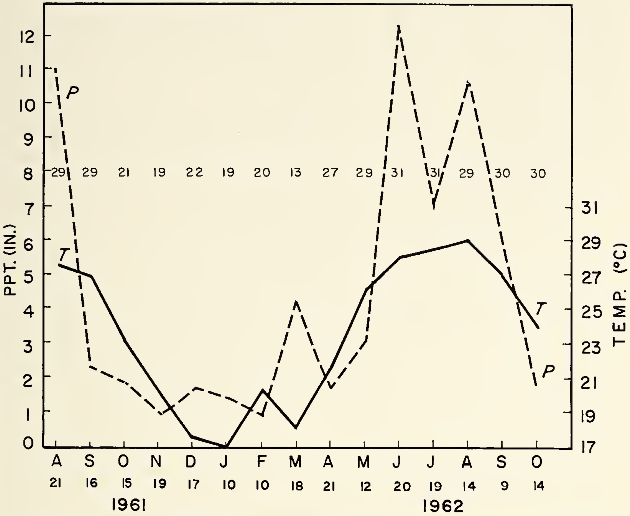


Fig. 2. Monthly mean precipitation and atmospheric temperature in the environment of Phosphate Pit Lake during 1961 and 1962. Figures inside the axes give atmospheric temperature at time of each visit. Numbers below the month abbreviations denote the date of visitation. Precipitation is given in inches following U. S. Weather Bureau policy.

All field work was done from an aluminum boat. Samples for chemical analyses were taken from the surface and at one-meter intervals to the bottom by means of a three-liter Foerst water sampler (Kemmerer-type). Samples returned to the laboratory for chemical analyses were stored in amber glass jugs that had been acid washed prior to use. Analyses in the laboratory were begun within 48 hours. Field determinations of methyl orange and phenolphthalein alkalinity, dissolved oxygen, and carbon dioxide were made immediately upon return to shore.

Chemical methods are listed below.

(1) Specific Conductance: Industrial Instrument Co., self-contained conductivity bridge with null indicator (American Public Health Association, Standard Methods, 1960).

(2) Calcium: Titrimetric with Calcein indicator and EDTA (Standard Methods, 1960).
(3) Total Hardness: Titrimetric with EDTA (Standard Methods 1960).
(4) Nitrate Nitrogen: Phenoldisulfonic acid method (Standard Methods, 1960).
(5) Magnesium: Difference in EDTA determination of Ca + Mg.
(6) Phosphate (ortho): Ammonium molybdate-stannous chloride method (Standard Methods, 1960).
(7) Aluminum: Hellige Water Comparator, color discs, and reagents from Hellige Corporation.
(8) Dissolved Oxygen: Alsterberg (Azide) modification of Winkler Method (Standard Methods, 1960).
(9) Free Carbon Dioxide: Titrimetric with NaOH and phenolphthalein (Standard Methods, 1960) and also calculated from *p*H and total alkalinity according to Rainwater and Thatcher (1960); the latter values are used in references to carbon dioxide.
(10) Total Alkalinity: Titrimetric with $H_2SO_4$ and methyl orange (Standard Methods, 1960).
(11) Phenolphthalein (Carbonate) Alkalinity: Titrimetric (Standard Methods, 1960).
(12) Hydronium Ion Concentration: Beckman Electric Pocket *p*H meter, replaced by Hellige Colorimetric Comparator Set with glass standards and indicators.
(13) Chloride: Mohr method (Standard Methods, 1960).
(14) Silicon Dioxide: Colorimetric molydosilicate method (Standard Methods, 1960).
(15) Iron: Phenanthroline method (Standard Methods, 1960).

Of the items listed above, (1) through (12) were determined monthly at one-meter intervals surface to bottom; items (13)-(15) were determined at 1 m intervals through the water column in August, 1961, January, April, August, and October, 1962. Because of technical difficulties, sodium and potassium were not assayed.

Physical features were measured as follows: stage data; personal gages; temperature: Whitney Electrical Underwater Thermometer, Whitney Instruments Co.; light transmission: Secchi disc and Whitney Underwater Daylight Meter with Deck Cell (Whitney Instruments Co.).

Certain biological components of the lakes were investigated and the methods are as follows.

*Chlorophyll a and chlorophyll b.* Acetone extraction and spectrophotometric method (Richards with Thompson, 1952, and Creitz and Richards, 1955). Absorbencies were read at 665, 645, and 630 m$\mu$ using a Bausch and Lomb "Spectronic 20" colorimeter with appropriate tubes. Samples were from one-meter intervals, surface to bottom, March-October, 1962. Banse and Anderson (1967) have found that values obtained by the Richards with Thompson equations are about 24 per cent higher than those derived by UNESCO (1966) and Parsons and Strickland (1963) procedures.

*Phytoplankton.* Concentrated from a 1.5-liter preserved sample of lake water by centrifuging at a moderate rate in a Foerst centrifuge. Aliquots of the concentrate were counted in a Sedgwick-Rafter cell at 100$\times$ magnification with a Whipple micrometer disc. From 5-10 fields were counted, depending upon density of organisms. In some instances, a total count of the entire contents of the cell was taken.

*Zooplankton.* Collection was monthly by means of a 10-liter plankton trap (Juday type) with a net of No. 25 bolting silk. Generally, samples were taken at the lake surface, mid-depth, and just above the bottom. In a number of instances, however, samples were taken at one-meter intervals, surface to bottom. In most determinations, total counts of zooplankton in a concentrated sample were made rather than estimation from aliquots.

*Benthic organisms.* Collection was monthly by means of a 6"$\times$6" (15.2$\times$15.2 cm) Ekman sampler at each station. The dredged material was washed over graded screens of mesh size sufficient to retain insect larvae and pupae, oligochaetes, and larger animals. Generally, two samples were screened at each station.

*Total seston.* Estimation was made by centrifuging 1.5 liters of lake water in a Foerst centrifuge and drying the centrifugate in an oven at 70° C for approximately 24 hours, or until quantitatively consistent weights taken 1-2 hours apart were obtained.

## Physical and Chemical Characteristics

*Temperature.* Phosphate Pit Lake was thermally stratified in

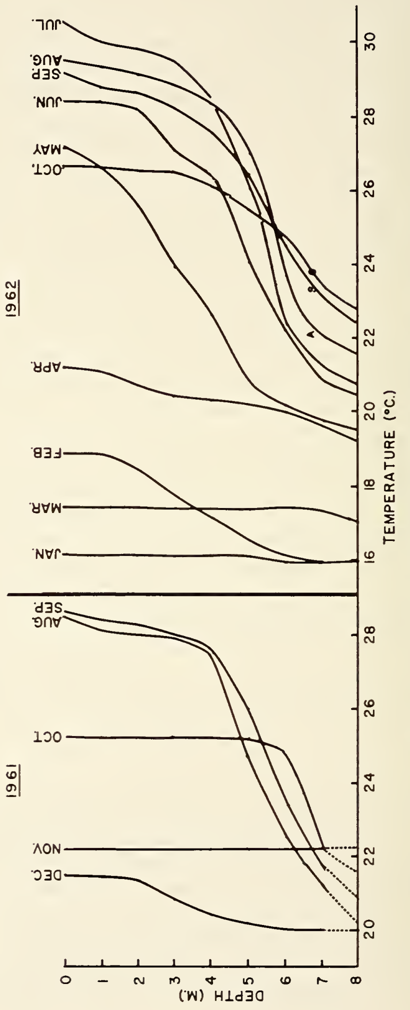


Fig. 3. Annual temperature cycle of Phosphate Pit Lake.

August, 1961, when the present study was begun, and remained so until October. Cooling began in August both years. The column was isothermal, or nearly so, from November, 1961, until May, 1962, when stratification was reestablished (Fig. 3). Lowest temperatures recorded were in January, at which time the water was almost uniformly 16 C surface to bottom. Surface waters were warmest in July, 1962, when the temperature reached 30.5 C. The mean ($N = 15$) surface temperature was 24.7 C. The range of bottom temperatures was much more narrow than that at the surface; at a depth of 7.5 m the minimum temperature was 15.9 C recorded in January and February, 1962, and the maximum was 22.7 C in October, 1962. The mean temperature at 7 m during the 15 months was 20.4 C.

The anomolous water temperature patterns of February and March, 1962, rest upon local climatological conditions. The average atmospheric temperature in the vicinity of the lake in February was 20 C, about 3° above normal, while the average for March was 17 C, or about 1° below normal (U. S. Dept. Commerce, 1963, pp. 174-183). Our data show that the air temperature at the time of our February visit was 20 C; in March it was 13 C.

On the basis of the vertical distribution patterns of oxygen and various ions described subsequently, and of temperature patterns shown here, we are led to conclude that this lake exhibits a high level of stability when stratified. The data show one circulation a year in winter and thus would qualify the lake as "warm monomictic" (Hutchinson and Löffler, 1956), although, admittedly, the hypolimnion is not extensive.

*Transparency.* The waters of Phosphate Pit Lake are generally turbid throughout the year. Secchi disc transparency was lowest during winter months and highest in summer (Fig. 4), the range being from 33 cm in February, to 110 cm in June, 1962. As pointed out previously, these measurements were made at roughly the same clock hour (0830-0930 hr) each month and the angle of incident radiation was greater in summer than in winter; a hazy overcast is also often present in the early hours of winter months.

Although measurements with the underwater light meter were taken only from February through October, 1962, there appears to be substantial agreement between these data (Table 1) and Secchi disc readings. Indeed, responses of the deck cell of the unit indicated that incident surface radiation at the time of the February-

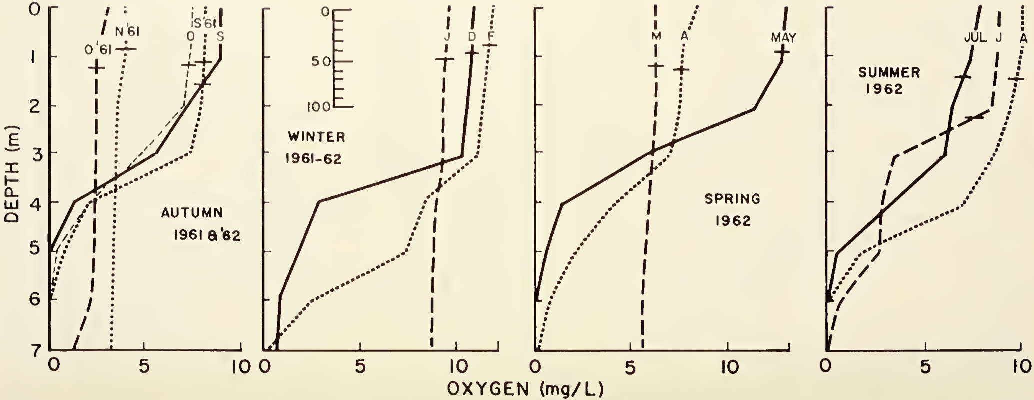


Fig. 4. Monthly patterns of dissolved oxygen content and Secchi disc readings through the water column of Phosphate Pit Lake. Cross bars on the graphs denote Secchi disc readings in cm in depth referable to the scale inset in coordinates for Winter.

TABLE 1

Light transmission, as per cent of surface illumination, through Phosphate Pit Lake, February-October, 1962

| Depth (m) | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.4 | 4.7 | 7.2 | 4.8 | 28.4 | 11.8 | 10.2 | 3.8 | 3.7 |
| 2 | 0.0 | 0.6 | 2.0 | 0.6 | 10.4 | 3.8 | 2.6 | 0.2 | 0.2 |
| 3 | | 0.0 | 0.6 | 0.0 | 4.3 | 1.0 | 0.4 | 0.0 | 0.0 |
| 4 | | | 0.0 | | 1.4 | 0.4 | 0.1 | | |
| 5 | | | | | 0.5 | 0.1 | 0.0 | | |
| 6 | | | | | 0.2 | 0.0 | | | |
| 7 | | | | | 0.0 | | | | |

March visits was about 33 per cent of that in summer. The greatest depth at which light was measured was 6 m; this was in June, when 0.2 per cent of the surface intensity was transmitted to that depth. The mean attenuation at a depth of 1 m during the period of study was 8.4 per cent of surface light.

*Specific Conductance and Total Hardness* (EDTA). Specific conductance, expressed as micromhos (reciprocal megohms) per cm at 25 C ($\mu$mhos), is proportional to the total electrolytes in water and serves as a quick introduction to the combined aspects of anions and cations in Phosphate Pit Lake. The reacting weight of each ion, milligram equivalents per liter (me/liter), can be obtained by multiplying the concentration of a given ion (mg/liter or ppm) by the reciprocal of its combining weight.

The mean of all conductance measurements made monthly at 1 m intervals of depth (N=119) during the 15-month study was 77 $\mu$mhos. Lowest conductance was in late summer and early autumn, 1961 and 1962, near the surface and at mid-depth (3-4 m) with values from 56-60 $\mu$mhos (Fig. 5). Highest ionic concentrations occurred during summer and early autumn in the near-bottom strata when in August, 1962, conductance reached 140 $\mu$mhos at 7 m, during a pronounced stratification. This developed in May, 1962, and existed into October, being a reflection of the vertical distribution of calcium and carbonate ions described below. During the period October, 1961-May, 1962, conductance was generally uniform from surface to bottom. The means of measurements made through the water column (N=8) monthly ranged from a high of

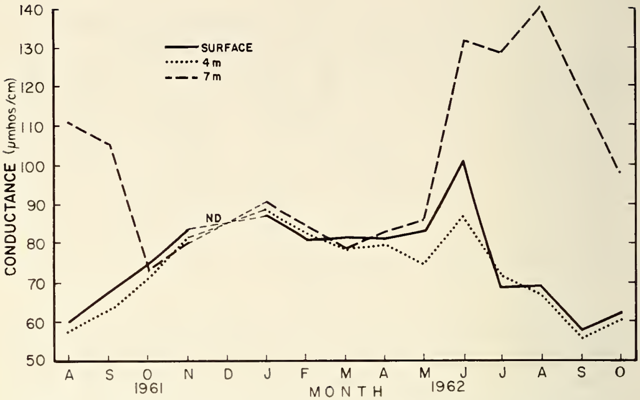


Fig. 5. Specific conductance monthly at surface, near-mid-depth (4 m), and bottom (7 m).

104 µmhos in June, 1962, to a low of 71 µmhos four months later in October.

Hardness (EDTA as mg/liter $CaCO_3$) varied from 47 at 7 m depth in July, 1962, to 17 mg/liter two months later at 4 m. The mean of all measurements (N = 120) was 28 mg/liter. The vertical distribution pattern of hardness exhibits, of course, the late summer-early autumn extreme highs correlated with conductance in the deeper waters and approximates bicarbonate alkalinity throughout. Noncarbonate hardness was present above 6 m depth at all times but disappeared from the bottom one-meter during the periods of high conductance and total hardness. Seasonal noncarbonate hardness at three depths is given in Table 2.

*Alkalinity.* Alkalinity was measured as methyl orange ("total") alkalinity, due to bicarbonates, and as the phenolphthalein equivalent of carbonate. Total alkalinity of the lake waters ranged from 70 mg/liter (1.15 me/liter) in July at 7 m, to 10 mg/liter (0.18 me/liter) at the surface in September, 1962. The mean total alkalinity in surface waters was 20; at 3 m it was 20; and at 7 m: 39 mg/liter. From November through April the water column was generally homogeneous in terms of total alkalinity, but with the onset of

TABLE 2

Monthly values of non-carbonate hardness (total hardness minus total alkalinity in mg/liter) in three levels of Phosphate Pit Lake

| Month | Surface | 4m | 7m |
|---|---|---|---|
| Aug | 4 | 5 | 0 |
| Sep | 8 | 7 | 0 |
| Oct | 5 | 5 | 5 |
| Nov | 1 | 1 | 2 |
| Dec | 3 | 2 | 0 |
| Jan | 4 | 3 | 5 |
| Feb | 5 | 5 | 0 |
| Mar | 2 | 2 | 1 |
| Apr | 6 | 6 | 4 |
| May | 8 | 7 | 0 |
| Jun | 5 | 6 | 0 |
| Jul | 8 | 6 | 0 |
| Aug | 6 | 3 | no data |
| Sep | 7 | 6 | 0 |
| Oct | 5 | 3 | 0 |

thermal stratification in May and continuing through October, total alkalinity below depths of 4-5 m increased greatly (Fig. 6).

Carbonates were detected in the upper 3 meters of the lake in August-September 1961, and in February and April-August, 1962 (Fig. 7). The February occurrence is interesting in that it correlates with the development of a slight thermal stratification in that month, but both disappeared the following month. The seasonal appearance and vertical pattern of carbonates in this lake are similar to the conditions in Lake Providence, Louisiana (Moore, 1950). Maximum carbonates came about in May when surface waters contained 15 mg/liter (0.51 me/liter) but this concentration decreased rapidly with depth to zero at 4 m. As will be shown subsequently, that was also the month of highest *p*H readings, oxygen concentrations, and chlorophyll *a* content. The mean carbonate content, when present, in surface waters was 5 mg/liter; at 3 m: 2 mg/liter.

*Hydronium Ion Concentration.* The *pH* of surface waters varied from 7.4 in March, to 9.6 in May, 1962, the mean throughout the 15 months being 8.4. At approximately mid-depth (4 m) the variation was not so great, being from 7.0-8.6 with an annual mean of 7.5. As shown in Fig. 8, this region was one of considerable decline

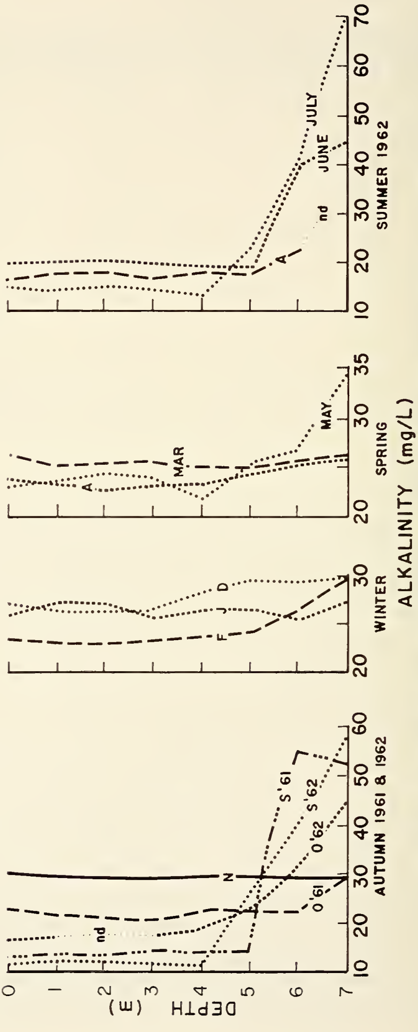


Fig. 6. Total alkalinity, monthly through the water column of Phosphate Pit Lake.

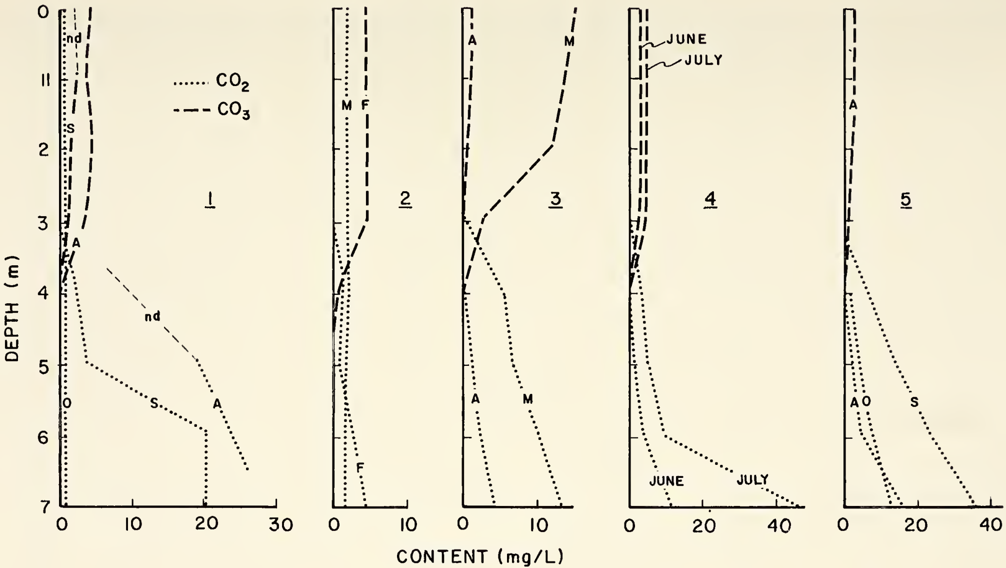


Fig. 7. Relationships of carbonate and carbon dioxide through the water column in selected months. Frame 1: August and September, 1961. Frame 2: February and March, 1962. Frame 3: April and May, 1962; Frame 4: June and July, 1962. Frame 5: August, September, and October, 1962. Values are in mg/liter.

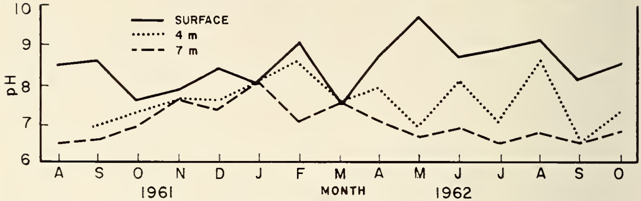


Fig. 8. Monthly variation in *p*H in three levels of Phosphate Pit Lake.

in *p*H toward more acid bottom waters which existed most of the time. The mean *p*H near bottom (7 m) was 6.9, ranging from 6.4-8.0; the high occurred in January, which was the only time the bottom layers were not at or below neutrality. Only in November, 1961, January, and March, 1962, was the water column found to be homogeneous or nearly so in terms of *p*H.

*Free Carbon Dioxide.* The carbon dioxide content in the upper 3 m of the lake was less than 1 mg/liter at all times except in March, 1962, when values of 1.6 mg/liter were obtained at all levels through the water column. From 4-7 m depth, however, considerable variation was found seasonally both at a given depth and in vertical perspective (Fig. 7). Highest concentrations of carbon dioxide were at 7 m in August and September, 1961, and during July and September, 1962; in the latter two months the values were 44 and 36 mg/liter respectively. Vertically, the waters were homogeneous and contained less than 1 mg carbon dioxide/liter at all depths in October-November, 1961, in January, 1962, and nearly so in December, 1961, there being only 3 mg/liter difference from surface to bottom. The mean carbon dioxide content at 4 m depth was 1.9, and at 7 m, 12 mg/liter.

*Dissolved Oxygen.* During the 15-month period, dissolved oxygen in the uppermost meter of the lake varied 9.9 mg/liter. From a low of 2.8 mg/liter (34 per cent saturation) in October, 1961, the concentration reached a high of 12.7 mg/liter in May, 1962. Surface waters failed to reach saturation during the periods September-November, 1961, and March-April, 1962. The mean concentration (N=15) of oxygen in surface waters was 8.4 mg/liter. Near mid-depth at 4 m, concentrations of 1.3-7.0 mg/liter prevailed, the mean of the monthly measurements being 4.1 mg/liter. Below 6 m depth anaerobic conditions existed in August and September, 1961, and from May through October, 1962. At 7 m the oxygen concentration was 8.7 mg/liter in January and 5.5 mg/liter in March, but throughout the other months it was less than 3 mg/liter, the mean for all months being 0.9 mg/liter.

Vertically through the lake the dissolved oxygen content was homogeneous, or nearly so, only in October and November, 1961, and in January and March, 1962 (Fig. 4). During the other months, marked oxygen stratification existed, and in some instances exhibited rather dramatic declines in concentration over a short vertical distance. In September, 1961, for example, the oxygen content decreased 5.1 mg/liter from 3-4 m; and in December the decline was 7.7 mg/liter in the same stratum. In May, 1962, the oxygen decreased 5.5 mg/liter between 2-3 m of depth. Moore (1950) reported similar phenomena in Lake Providence, Louisiana, and emphasized that the rapid decline in oxygen often occurred above the thermocline, as was also the case in Phosphate Pit Lake (Fig. 4). Moore suggested that such conditions would indicate incomplete mixing at times in the epilimnion as a result of protection from winds. The small surface area and the steep banks surrounding the pit would tend to reduce wind effects.

*Calcium and Magnesium.* The calcium content of the lake waters fluctuated seasonally, both at any given depth and vertically with considerable magnitude. Minimum concentration of the ion (8.8 mg/liter) was in September, 1962, at 4 m, while the maximum (34.9 mg/liter) existed at the same time at 7 m. As shown in Fig. 9, calcium was lowest in surface waters in summer and remained rather uniformly near 20 mg/liter during the remainder of the year. The mean of 15 surface determinations was 16.3 mg/liter (0.79 me/liter). Generally, the amounts of calcium seasonally at mid-depth varied little from those near surface, the mean at 4 m being 15.8 mg/liter. During summer and early autumn, however, concentrations were increased greatly below 5 m resulting in a mean of 24.8 mg/liter (1.21 me/liter) at 7 m. From October, 1961, through May, 1962, the calcium content of the lake was nearly uniform from surface to bottom (Fig. 9), but during summer, differences through the water column varied about 15.5 mg/liter, and in September, 1962, 24.6 mg/liter from surface to 7 m.

Magnesium concentration varied only from 7.0 mg/liter in March 1962, at 4 m to 15.0 mg/liter recorded the previous Septem-

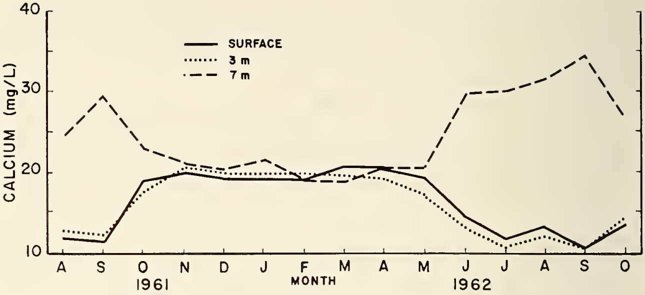


Fig. 9. Seasonal variations in calcium content in three levels of the lake.

ber. The magnesium maximum in surface waters was 12.6 mg/liter in May, 1962, the minimum being 7.7 mg/liter in March preceding. The mean magnesium content of the surface stratum (N = 15) was 9.9 mg/L (0.81 me/liter); the mean at mid-depth was approximately the same. At 7 m magnesium ranged from 7.9 mg/liter in March, 1962, to 17.2 mg/liter the following July. The mean of monthly measurements at that depth was 11.7 mg/liter (0.95 me/liter) reflecting slightly higher concentrations in late summer than during the remainder of the year.

*Aluminum, Silica, Iron, and Chloride.* Although analyses were made monthly over the 15-month period, aluminum was detected only in September-October, 1961, February-March, and May-June, 1962. The highest concentration was 0.09 mg/liter in the bottom 2 m in February; this was the only period when the ion was found at all depths, the mean through the water column being 0.05 mg/liter (0.005 me/liter). The mean of all detectable quantities (N = 34) was 0.03 mg/liter.

Analyses for silica (as $SiO_2$) were made in August, 1961, and in January, April, August, and October, 1962; the ion was present at all depths in each of the months. Highest concentrations in surface waters, as well as through the vertical column, were in January (Table 3), the mean through the column in January was 4.0 mg/liter. Greatest amounts in deep waters were in August, 1961 and 1962. The mean of surface waters was 2.7 and at 7m, 3.4 mg/liter. Lowest quantities occurred in October, 1962, at which time the

TABLE 3

Silica, iron, and chloride (mg/liter) in Phosphate Pit Lake in August, 1961, and in January, April, August, and October, 1962

| Mineral | Depth (m) | Aug | Jan | Apr | Aug | Oct |
|---|---|---|---|---|---|---|
| $SiO_2$ | 0 | 2.4 | 4.9 | 2.9 | 2.1 | 1.3 |
| | 1 | 3.2 | 4.9 | 2.7 | 2.3 | 1.1 |
| | 2 | 2.8 | 3.5 | 2.8 | 2.0 | 1.1 |
| | 3 | 2.5 | 3.5 | 2.8 | 2.5 | 1.2 |
| | 4 | 2.4 | 3.9 | 2.5 | 1.8 | 1.1 |
| | 5 | 2.2 | 3.9 | 2.9 | 2.0 | 1.4 |
| | 6 | 2.2 | 3.9 | 3.0 | 2.2 | 1.4 |
| | 7 | 4.1 | 3.8 | 3.3 | 4.2 | 1.7 |
| Fe | 0 | 0.05 | 0.12 | 0.07 | 0.10 | — |
| | 1 | 0.08 | 0.11 | 0.07 | 0.10 | — |
| | 2 | 0.09 | 0.04 | 0.07 | 0.09 | — |
| | 3 | 0.08 | 0.03 | 0.04 | 0.09 | — |
| | 4 | 0.04 | 0.03 | 0.07 | 0.09 | — |
| | 5 | 0.03 | 0.04 | 0.04 | 0.09 | — |
| | 6 | 0.06 | 0.01 | 0.04 | 0.12 | — |
| | 7 | 0.17 | 0.02 | 0.04 | 0.26 | — |
| Cl | 0 | 8.5 | 7.3 | 8.5 | 6.2 | 5.7 |
| | 1 | 8.9 | 7.5 | 7.5 | 6.4 | 6.2 |
| | 2 | 8.5 | 7.5 | 8.3 | 5.8 | 6.2 |
| | 3 | 8.8 | 7.8 | 7.8 | 7.0 | 6.2 |
| | 4 | 8.4 | 7.6 | 7.0 | 6.4 | 5.6 |
| | 5 | 8.3 | 7.8 | 7.1 | 6.0 | 6.2 |
| | 6 | 8.3 | 8.0 | 8.0 | 6.6 | 5.7 |
| | 7 | 8.5 | 7.9 | 7.1 | — | 5.3 |

column mean was 1.3 mg/liter. The mean of all determinations (N=40) was 2.6 mg/liter.

Iron was determined through the water column in August, 1961, and in January, April, and August, 1962. In surface waters the iron content ranged from 0.05 mg/liter in August, 1961, to 0.12 mg/liter in January following (Table 3); the mean (N=4) at the surface was 0.08 mg/liter. Near bottom, the mean iron concentration was 0.12 mg/liter, resulting mainly from decidedly higher values obtained in August, 1961 (0.17 mg/liter) and again the following August (0.26 mg/liter). Vertically, the amount of iron was highest in August, 1962, at which time the mean of eight analyses was 0.12

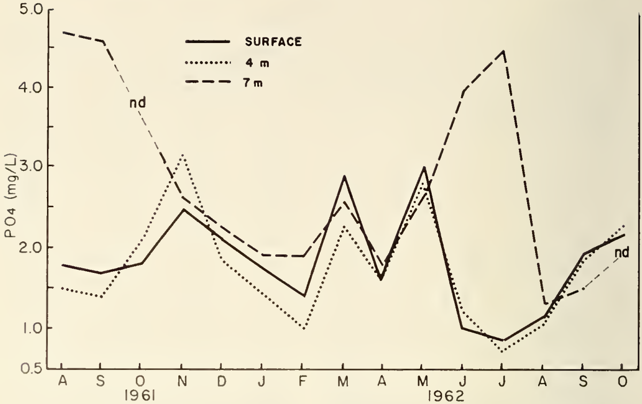


Fig. 10. Seasonal variations in orthophosphate content in three levels of the lake.

mg/liter. In August preceding, however, the mean through the column was 0.07 mg/liter, while the January and April means were 0.05 mg/liter in each of the months. The mean of all determinations (N=32) was 0.07 mg/liter.

Chloride was measured in August, 1961, and in January, April, August, and October, 1962. Greatest concentration through the column occurred in August, 1961 (Table 3), when the mean was 8.5 mg/liter. The lowest vertical content was in October, 1962, the mean being 5.9 mg/liter. Seasonally, chloride varied little with depth, the mean for surface waters amounting to 7.2 mg/liter; at 4 m: 6.6; and at 7 m: 7.2 mg/liter. The mean of all measurements (N=39) was 7.2 mg/liter (0.20 me/liter).

*Orthophosphate and Nitrate.* The highest concentrations of phosphate (ortho) in the lake were detected in August-September, 1961, and in June-July, 1962, when values from 4.0-4.7 mg/liter were obtained. Minimum quantities were found during the period June-August, in the upper 4 m, the range being 0.7-1.1 mg/liter. The mean of all determinations (N=119) for phosphate was 2.0 mg/liter. Throughout the 15-month study, the phosphate content in surface and mid-depth waters differed little (Fig. 10), the mean for each stratum being 1.8 mg/liter. In the zone below 6 m, how-

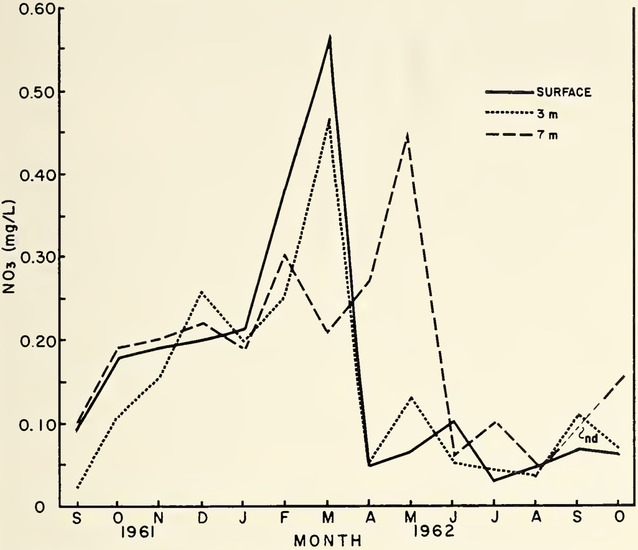


Fig. 11. Seasonal variation in nitrate content at three levels in Phosphate Pit Lake.

ever, the concentration varied considerably from 1.1 mg/liter to the maxima noted above. The mean content through the seasons at 7 m was 2.7 mg/liter. Through the water column, the lake waters were richest in phosphate in May, the mean from surface to bottom being 3.1 mg/liter. Three months later, however, this had decreased to 1.2 mg/liter.

Nitrogen as nitrate fluctuated considerably both vertically from month to month (Fig. 11) and seasonally at the various depths. The highest values through the water column were taken in March, 1962, when the surface waters contained 0.57 mg/liter and the deeper water 0.21 mg/liter, the mean being 0.39 mg/liter. Minimum concentrations occurred in July and August, 1962, at which times the mean for each month was 0.04 mg/liter. Surface waters varied from a high of 0.57 mg/liter in March, 1962, to 0.03 mg/liter the following July, the mean for 14 months being 0.15 mg/liter. The mean for the same time at a depth of 4 m was 0.13 mg/liter. Deeper waters, at 7 m, contained somewhat higher quantities of nitrate, the mean being 0.18 mg/liter.

## BIOLOGICAL CHARACTERISTICS

*Phytoplankton.* Data on phytoplankton are available for the period August, 1961, through August, 1962. The most persistent algae during this period were blue-greens, *Anacystis* sp. and *Anabaenopsis* sp., the former being present from surface to bottom at all times but showing no particular seasonal pattern in variation in density. *Anabaenopsis* was not recorded in January, 1962, and concentrations were generally low during the winter months. In late summer, however, the density reached $270 \times 10^5$ filaments per liter in 1961 (August) and $110 \times 10^5$ filaments/liter in August, 1962. Another blue-green, *Chroococcus* sp., was present from August through December, 1961, reaching maximum density of $8.5 \times 10^5$ cells/liter in the latter month at a depth of 7 m.

The most conspicuous Chlorophyta in Phosphate Pit Lake were *Ankistrodesmus falcatus* var. *spirilliformis* G. S. West, *Scenedesmus* sp., *Tetraëdron* sp., and *Coelastrum sphaericum* Naeg. The occurrence of *Ankistrodesmus* appeared to be decidedly seasonal, for it was present in August, 1961, in concentrations of $1300 \times 10^5$ cells/liter at the surface and $3300 \times 10^5$ cells/liter at 4 m, but was not recorded again until the following May. In that month the count was $83 \times 10^5$ cells/liter in surface waters and it increased to $230 \times 10^5$ in July. By August the density in surface waters decreased to $150 \times 10^5$ cells/liter. During the summer months the count of *Ankistrodesmus* decreased directly with depth such that at 7 m the population ranged from $11 \times 10^5$ to $70 \times 10^5$ cells/liter. *Scenedesmus* sp. was present through the water column in October and December, 1961, and from February through June, 1962. In the surface waters the concentration of the alga ranged from $4.1 \times 10^5$ cells/liter in December, to $0.5 \times 10^5$ cells/liter in June; at a depth of 7 m the lowest counts were $0.7 \times 10^5$ in February and June, and the highest, $7.6 \times 10^5$, in December. The occurrence of *Tetraëdron* coincided with that of *Ankistrodesmus* but continued later through July and August, 1962. In the upper waters the lowest population density of *Tetraëdon* was $0.3 \times 10^5$ cells/liter in April, while the highest was

$12 \times 10^5$ in July following. Generally, the density of the alga decreased with depth such that counts at 7 m ranged from $1.3 \times 10^5$ to $3.9 \times 10^5$ cells/liter. *Coelastrum sphaericum* was present in our samples in November, 1961, and during April-June, 1962, although absent in surface waters during May and June. The highest concentration of the species was recorded at 4 m in April, 1962, the count being $22 \times 10^5$ colonies (coenobia)/liter.

Diatoms (Chrysophyta), mostly *Synedra,* but some *Navicula,* were present in the lake at all depths throughout the year, although the density of the aggregations varied greatly. Autumn seemed to be the season of most sparse populations; at this time our counts were of the order of $0.18 \times 10^5$ to $2.1 \times 10^5$ cells/liter. During the summer, however, diatom concentrations increased decidedly, up to the order of $5.9 \times 10^5$ to $12 \times 10^5$ cells/liter, with a maximum being reached in June, 1962, when the density at 7 m depth was $53.8 \times 10^5$ cells/liter. This was associated with a marked increase in numbers with depth; the density in surface waters was $15 \times 10^5$ and at 4 m, $38 \times 10^5$ cells/liter. Otherwise, no distinctive depth distribution pattern of diatoms was observed. The greatest variety of phytoplankters was noted in May, 1962, at which time all of the aforementioned forms except *Chroococcus* were present.

*Chlorophyll a.* Estimates of chlorophyll *a* were obtained through the water column monthly from February through October, 1962. In general the greatest concentrations at all depth were in the March-May period (Fig. 12). Chlorophyll *a* in surface waters ranged from 54.6 mg/m$^3$ in May to 6.1 mg/m$^3$ the following July, the mean for nine months being 23.6 mg/m$^3$. Near mid-depth the content of the pigment varied from 55.6 mg/m$^3$ in May to 5.8 mg/m$^3$ in September, the mean for the period at this depth being 26.3 mg/m$^3$. At the bottom, the highest value (46.4 mg/m$^3$) was determined in May, and the lowest (3.1 mg/m$^3$) in February preceding; the mean at 7 m was 19.9 mg/m$^3$. Vertically through Phosphate Pit Lake the chlorophyll *a* content was maximum in May, when the mean from surface to bottom was 68.1 mg/m$^3$. Minimum concentration occurred in September, the mean through the column being 6.3 mg/m$^3$.

*Zooplankton.* The diel zooplankton of Phosphate Pit Lake was composed almost entirely of Rotifera and nauplii of Copepoda. We

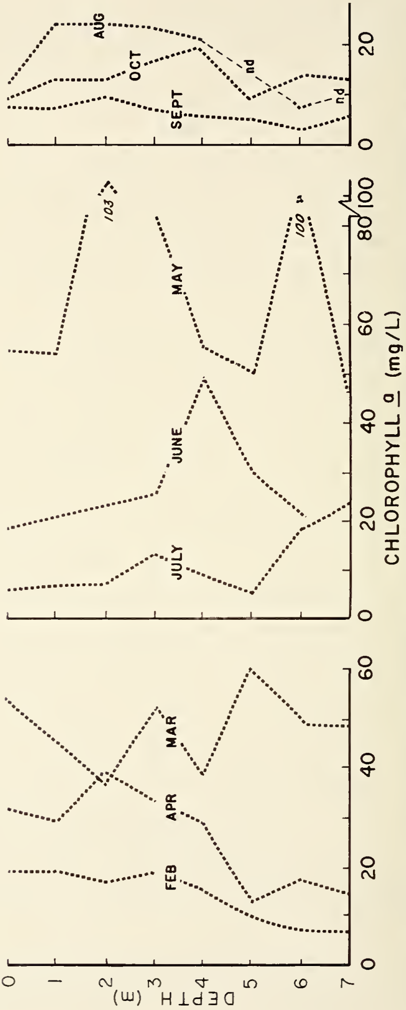


Fig. 12. Vertical aspects of chlorophyll *a* content, February through October, 1962, in Phosphate Pit Lake.

TABLE 4

Monthly counts of Rotifera (individuals per liter) at three levels in Phosphate Pit Lake

| Month | Surface | 3-4 m | 7-7.5 m |
|---|---|---|---|
| Aug 1961 | 13 | 510 | 200 |
| Sep | 190 | 90 | 13 |
| Oct | 120 | 70 | 0 |
| Nov | 70 | 110 | 115 |
| Dec | 1 | 0 | 0 |
| Jan 1962 | 1 | 1 | 1 |
| Feb | 90 | 45 | 0 |
| Mar | 96 | 160 | 122 |
| Apr | 6 | 0 | 0 |
| May | 563 | 1510 | 666 |
| Jun | 77 | 77 | 6 |
| Jul | 6 | 13 | 6 |
| Aug | 32 | 102 | 90 |
| Sep | 6 | 13 | 6 |
| Oct | 0 | 0 | 0 |

emphasize the day-time aspect, for subsequent studies of diurnal migrations of *Mesocyclops edax* in winter in a nearby phosphate pit have revealed sizable populations of this copepod, together with larvae of *Chaoborus*, from surface to bottom during early morning hours before sunrise (Reid and Blake, 1970).

The population density of rotifers varied considerably, both seasonally at a given depth and vertically within the lake (Table 4). In December, 1961, rotifers were sparse in the upper waters and absent in deeper layers; in October, 1962, no rotifers were taken in the sampling. In January, 1962, the census was only one individual per liter (ind/liter). As shown in the Table, the highest density of rotifers occurred in May, 1962, when the mid-water sample contained 1510 ind/liter; the mean of the counts at three levels was 913 ind/liter. The mean of all monthly data for surface, mid-depth, and bottom were 91, 225, and 137 ind/liter, respectively.

Copepod nauplii were present in the lake throughout most of the year although in drastically reduced numbers in summer and early fall (Table 5); none was taken at any depth in July. The mean density of the surface population for the months when the animals were present was 59 ind/liter. At mid-depth the mean was 58 ind/liter, and at bottom: 35 ind/liter.

TABLE 5

Monthly census of Copepoda (individuals per liter) at three depths in Phosphate Pit Lake

| Month | Surface | 3-4 m | 7-7.5 m |
|---|---|---|---|
| Aug 1961 | 1 | 10 | 4 |
| Sep | 32 | 58 | 0 |
| Oct | 13 | 26 | 6 |
| Nov | 64 | 110 | 51 |
| Dec | 198 | 90 | 5 |
| Jan 1962 | 51 | 76 | 38 |
| Feb | 134 | 70 | 45 |
| Mar | 70 | 90 | 122 |
| Apr | 83 | 198 | 77 |
| May | 0 | 64 | 70 |
| Jun | 1 | 6 | 1 |
| Jul | 0 | 0 | 0 |
| Aug | 0 | 1 | 1 |
| Sep | 0 | 6 | 1 |
| Oct | 1 | 2 | 1 |

Adult calanoid copepods were found in quantities greater than one per liter only from November, 1961, through April, 1962. During that period the animals were present at all depths, the maximum density occurring in December when the count in surface samples was 108 ind/liter, at mid-depth: 83 ind/liter; but only 2 ind/liter at the bottom. The mean density in the five months surface samples in which the plankter was present was 25 ind/liter; in six samples from mid-depth: 24 ind/liter; and at the bottom: 11 ind/liter.

Adult cyclopoid copepods were even more rare than calanoids in Phosphate Pit Lake. In surface waters *Mesocyclops edax* occurred only in our samples of December, 1961, and January-February, 1962; 13 ind/liter in the first period and 1 ind/liter in each of the two months of 1962. In the mid-water region this plankton was found in numbers greater than one per liter in September, October, and December, 1961, and in March, 1962; the maximum was 32 ind/liter in October. In the bottom waters we recorded more than one cyclopoid per liter only in October (13 ind/liter) and February-March, 1962 (4 ind/liter) each month. The migratory behavior of *M. edax* is apparently quite erratic, for in a 24-hour diurnal study of plankton in a near-by pit on 8 January, 1964, noon samples from 4-6 meters depth contained nine of the copepods; 12 days later the

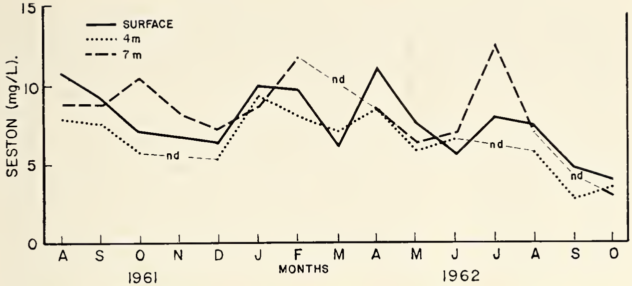


Fig. 13. Monthly variation in total seston content of Phosphate Pit Lake.

density of the species ranged from 10 ind/liter at 4 m to 27 ind/liter at 6 m (Reid and Blake, 1970).

The absence of Cladocera proved to be one of the more astounding findings in this study. At mid-depth in May, 1962, our count indicated one individual per liter, and this was the only occurrence of what is usually considered to be a characteristic planktonic crustacean. Our unpublished data for a natural lake (Scott) in the phosphate region of Central Florida reveal an identical situation, while in Clear Lake, a solution basin, cladocerans were present throughout the year in densities ranging up to nearly 400 individuals per liter.

*Seston.* Total seston, here defined as all living and non-living particulate matter in the water, varied in the upper waters about 6 mg/liter during the 15 months of study. The seasonal variation in seston content of bottom waters, on the other hand, was of the order of 11 mg/liter and exhibited two maxima, in February and in July, 1962 (Fig. 13). Each of these coincided with a decrease in seston mass in upper waters and followed upon noticeable pulses of seston in the upper layers. Over the 15-month period the mean seston content of surface waters was 7.6 mg/liter; at mid-depth the mean was 7.5 mg/liter; and near bottom: 8.9 mg/liter. These figure would indicate that although phyto- and zooplankton densities fluctuate through an annual cycle, as does the amount of allochthonous materials introduced seasonally with surface run-off from rainfall, the lake maintains a relatively high level of vertical homogeneity in the standing crop of seston.

*Benthos.* The bottom of Phosphate Pit Lake is composed of fine, flocculent material of particle size that easily washes through a screen of 20 meshes per centimeter. No macro-phytobenthos existed.

During our study, the zoobenthos of sufficient size to be retained in the aforementioned screen consisted mostly of larvae of *Chaoborus* sp. (Diptera). They were present in all months but the population density varied seasonally. The months from November, 1961, through March, 1962, were the times of greatest abundance of the larval forms, the maximum being reached in December when the count was 12,169 individuals per $m^2$. During the other months of the winter the density ranged from 4,000 to slightly over 5,000 ind/$m^2$. The population was most sparse in April, 1962, when sample counts indicated about 600 ind/$m^2$; this however, was also a period of emergence of the insect, and numerous exuvia were observed over the surface of the lake and on the shore.

In the diurnal studies in the near-by pit noted above, *Chaoborus* larvae became planktonic at night, appearing in the bottom two meters in January at sundown (1800 hr). By 2100 hr they were present through the entire water column and remained there until near sunrise.

The pupae of *Chaoborus* came into our samples only in September, 1961 (30 ind/$m^2$), February (20 ind/$m^2$), March (120 ind/$m^2$), and June (20 ind/$m^2$), 1962. Larval forms of another dipteran, *Tendipes* sp. were taken during winter, the highest density being 800 ind/$m^2$ in December, 1961. Cyclopoid and calanoid copepods were common to abundant in samples throughout the year, and small oligochaetes were taken occasionally; no quantitative estimates were made, however.

## SUMMARY AND CONCLUSIONS

Phosphate Pit Lake is a small, eutrophic, monomictic body of water artificially produced as result of mining for phosphatic limestone in South Central Florida. Maximum depth to a soft flocculent bottom is 7.5-8.0 m.

Throughout the period of study (August, 1961 through October, 1962), transparency was generally low. The maximum was in June, at which time the depth at which a Secchi disc disappeared was

110 cm, and photocell measurements indicated 0.2 per cent of surface illumination at 6 m.

During the period of investigation, the lake exhibited rather stable thermal and chemical stratification from May through October, although oxygen stratification occurred in some winter months also. The hypolimnion was restricted, generally, to about the bottom-most 2 meters. During summer and early autumn, hypolimnetic waters became anaerobic, and carbon dioxide appeared in significant amounts, resulting in layering of carbonates in the upper waters and carbon dioxide in the lower strata. The quantity of dissolved substances, such as calcium, magnesium, phosphate, and bicarbonates, increased greatly in the deeper region in summer. This resulted in a decidedly higher specific conductance in the hypolimnion. Total hardness of the lake ranged about a mean of 28 mg $CaCO_3$/liter.

The nitrate content at all depths in the lake was highest during winter months, but decreased rapidly in the upper waters in spring as phytoplankton populations increased. This was followed by a marked reduction of the ion in deeper waters in June, and a low but nearly uniform nitrate content existed through the water column until autumn.

As might be expected in view of the origin and location of the lake, the phosphate content was generally high (up to nearly 5 mg/liter) but varied seasonally. During winter and spring, the concentration of this ion was rather uniform from surface to bottom, but in summer the hypolimnetic waters were much richer than the upper strata in phosphate. As shown in Fig. 14, the monthly pattern of mean phosphate through the water column exhibited trends similar to those of chlorophyll and nitrate.

The *p*H of upper waters was consistently above neutrality, becoming near and above *p*H 9 in summer. Deeper waters were nearly neutral throughout the 15-month period.

From November through April, Phosphate Pit Lake was vertically isometric, or nearly so, in total (methyl orange) alkalinity measurements, varying only slightly from near 26 mg/liter. During the remainder of the year, however, marked stratification existed and the alkalinity of strata below 4.5 m greatly exceeded that of upper waters. Carbonate (phenolphthalein) alkalinity was present in waters above 4-5 m from April through August, during which

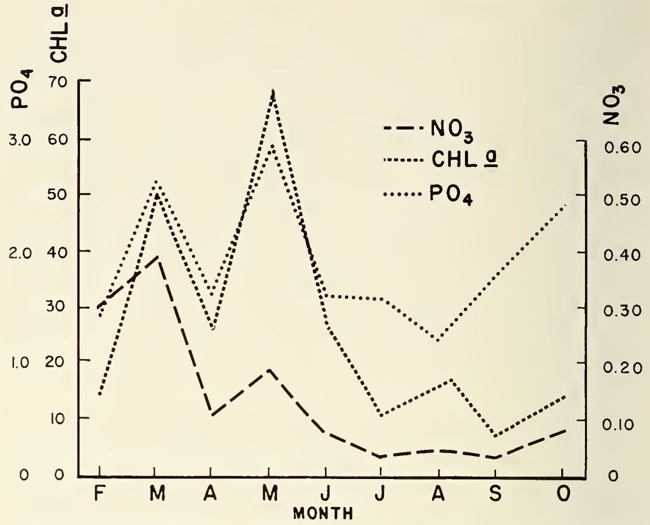


Fig. 14. Comparison of annual cycles of nitrate, phosphate, and chlorophyll *a* in Phosphate Pit Lake. Monthly values represent the mean content of each substance vertically through the water column determined at one-meter intervals, surface to bottom (7 m). All values are expressed as mg/liter.

time carbon dioxide was absent, doubtlessly having been taken up in algal photosynthesis.

Silica occurred in highest quantities in winter and decreased through spring and summer, probably being incorporated into valves of diatoms as these algae increased in number. Iron and chloride concentrations remained essentially uniform over the year.

Chlorophyll *a* was determined vertically through the water only from February through October, 1962. Highest quantities occurred in March, May, and June. In March, maxima existed at depths of 3 m and 5 m; in June, a maximum occurred at 4m; and in May, maxima were at 2 m and 6 m. Seasonally, the monthly mean chlorophyll content through the water column followed closely the pattern of phosphate and nitrate (Fig. 14).

Surface temperatures varied from 16.2 C in January to 30.5 C in July; bottom waters ranged from 15.9 C in January and February to

22.7 C in October. As indicated above, the lake was thermally stratified from May through October, and nearly homothermal during winter. All data pointed toward a rather high degree of stability during stratification.

The dissolved oxygen content of the lake was highest in May in surface waters (12.7 mg/liter). In the upper strata, the concentration failed to reach saturation in September and November, 1961, and during the period March-April, 1962. In 1961, however, stratification was not present in October, and, interestingly, oxygen stratification reappeared during winter in December and February. Throughout the summer the oxycline extended from about 2 m to near 4 m of depth. Anaerobic states prevailed below 5 m in August-September, 1961, and from May through October, 1962.

Free carbon dioxide in significant amounts was confined to waters of the lake below 4 m. Considerable season variation in the content of the gas occurred, the highest concentrations being in late summer and early autumn (up to 44 mg/liter). Vertical distributional relationships between carbon dioxide and carbonates were noted previously.

Biologically, the lake appeared to be quite productive, at least insofar as the seasonal standing crop of phytoplankton was concerned. In winter the populations were sparse, consisting predominantly of *Anacystis* sp., *Anabaenopsis* sp., *Chroococcus* sp., *Scenedesmus* sp., and diatoms. During spring however, the numbers and kinds of algae increased, the plankton being marked conspicuously by the presence of large numbers of *Ankistrodesmus falcatus, Coelastrum sphaericum,* and *Tetraëdron* sp.

The diel zooplankton community consisted, in the main, of Rotifera and immature Copepoda. The rotifer population dwindled considerably in winter but increased greatly during early summer. A most glaring aspect of the zooplankton was the absence of adult Copepoda and Cladocera. Observations in a near-by pit revealed diurnal vertical migrations by large numbers of *Mesocyclops edax,* a cyclopoid copepod, thus suggesting differences in the composition of zooplankton from day to night.

Total seston contained in the lake at all levels ranged generally from about 5-10 mg/liter. The content of seston in deeper waters rose to nearly 13 mg/liter in July, but decreased significantly in autumn.

Zoobenthic animals retained in a 20 mesh/cm screen were mainly *Chaoborus* sp., a dipteran; the population density reached slightly over 12,000 individuals per square meter in December. This organism becomes planktonic at night. Larvae of another dipteran, *Tendipes* sp., entered the collections during winter, and cyclopoid and calanoid copepods were common to abundant in the benthos throughout the year. Oligochaetes were taken occasionally.


## ACKNOWLEDGMENTS

We are pleased to acknowledge the assistance of Dr. Francis Drouet, Academy of Natural Sciences, Philadelphia, and Dr. L. A. Whitford, North Carolina State College, Raleigh, in the identification of algae, and Dr. G. A. Cole, Arizona State University, Tempe, for identifying copepods. Appreciation is accorded Dr. A. M. Laessle, University of Florida, Gainesville, for criticisms of portions of an earlier manuscript; and to the U. S. Geological Survey, Ocala, Florida, and Mr. U. K. Custred, American Cyanamid Corporation, Mulberry, Florida, for useful data. We are also indebted to former students Janet Auermann, Sheila Most, Roger Porter, Norman Blake, and Grover Wrenn for plankton counts, chlorophyll determinations, chemical analyses, and field aid. Under the supervision of the junior author participating in a program sponsored by the American Chemical Society, some of the chemical analyses were made by students of Mr. Walter Swan, Northeast High School, St. Petersburg; to them we are grateful. Financial support was provided by the Florida Presbyterian College Research Committee and National Science Foundation (Grant No. 17865).


## LITERATURE CITED


AMERICAN PUBLIC HEALTH ASSOCIATION. 1960. Standard methods for the examination of water and wastewater. 11th ed. American Public Health Association, New York.

BANSE, K., AND G. C. ANDERSON. 1967. Computations of chlorophyll concentrations from spectrophotometric readings. Limnol. Oceanog., vol. 12, pp. 696-697.

CREITZ, G. I., AND F. A. RICHARDS. 1955. The estimation and characterization of plankton populations by pigment analyses. III. A note on the use of "Millipore" membrane filters in the estimation of plankton pigments. Jour. Marine Res., vol. 14, pp. 211-216.

HUTCHINSON, G. E., AND H. LÖFFLER. 1956. The thermal classification of lakes. Proc. Nat. Acad. Sci., vol. 42, pp. 84-86.

MOORE, WALTER G. 1950. Limnological studies of Louisiana lakes. 1. Lake Providence. Ecology, vol. 31, pp. 86-99.

PARSONS, T. R., AND J. D. H. STRICKLAND. 1963. Discussion of spectrophotometric determinations of marine-plant pigments, with revised equations for ascertaining chlorophylls and carotenoids. Jour. Marine Res., vol. 21, pp. 155-163.

RAINWATER, F. H., AND L. L. THATCHER. 1960. Methods for collection and analysis of water. U.S. Geol. Surv. Water Supply Paper 1454.

REID, G. K., AND N. J. BLAKE. 1970. Diurnal zooplankton ecology in a phosphate pit lake. Quart. Jour. Florida Acad. Sci., vol. 32, no. 4, pp. 275-284.

RICHARDS, F. A., WITH T. F. THOMPSON. 1952. The estimation and characterization of plankton populations by pigment analyses. II. A spectrophotometric method for the estimation of plankton pigments. Jour. Marine Res., vol. 11, pp. 156-172.

SHIRLEY, L. E., AND R. O. VERNON. 1960. The mineral industry of Florida. Minerals Yearbook. U.S. Bureau of Mines, vol. 3, pp. 263-293.

UNESCO. 1966. Monographs on oceanographic methodology. 1. Determination of photosynthetic pigments in sea-water. United Nations Educational, Scientific and Cultural Organization, Paris.

UNITED STATES DEPARTMENT OF COMMERCE. 1963. Climatological data for 1961.

*Division of Mathematics and Natural Sciences, Florida Presbyterian College, St. Petersburg, Florida 33733; Department of Chemistry, University of North Carolina at Asheville, Asheville, North Carolina.*